Physical origins of slow traps for ALD high-k dielectrics on GeO_x/Ge interfaces

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Introduction Ge with higher electron and hole mobility is an attracting channel material for next generation MOSFETs[1]. While Al_2O_3/GeO_x/Ge and HfO_2/Al_2O_3/GeO_x/Ge structures fabricated by PPO (plasma post oxidation) have been reported as one of the realistic gate stacks with very thin EOT [2-3], a large amount of slow traps existing at the Ge MOS interfaces and resulting inferior reliability have been one of the most critical remaining issues for Ge CMOS realization [4-6]. We have recently found that the slow traps for electrons could exist inside GeO_x formed by PPO [7]. However, the physical origin of the slow trap generation for electrons and holes has not been understood yet. In this study, we systematically compare the slow trap density of electron and holes for the Al_2O_3/GeO_x/Ge interfaces with different GeO_x thickness prepared by post or pre plasma oxidation for ALD Al_2O_3/Ge stacks. Also, we examine the influence of high-k post deposition on ΔN_{st} in the high-k/GeO_x/Ge MOS interfaces to study the physical origin of slow traps.

Experiments (100) Ge wafers were cleaned by de-ionized water, acetone and HF. After the pre-cleaning, plasma pre-oxidation was performed by using ECR plasma of Ar (9 sccm) and O_2 (3 sccm) at 300 °C under 650 W microwave power for 1-10 s. Subsequently, 1.5- to 2.4-nm-thick Al_2O_3 were deposited on 0.67- to 1.11-nm-thick GeO_x/Ge at 300 °C by ALD. Also, 10-nm-thick Al_2O_3, HfO_2, La_2O_3 or Y_2O_3 were deposited on 1.4-nm-thick GeO_x/Ge structures at 300 °C. Post deposition annealing (PDA) was performed for 30 min at 400 °C in N_2 ambient, followed by formation of 100-nm-thick Au gate electrodes and 100-nm-thick Al back contacts by thermal evaporation.

Results and Discussions Fig. 1(a) and (b) show the comparison in ΔN_{st} of 1.5-nm-thick Al_2O_3/GeO_x/n- and p-Ge, respectively, between plasma post- and pre-oxidation with an EOT ~1.5-nm-thick. It is found that ΔN_{st} is significantly higher in the n-Ge MOS capacitor formed for plasma post-oxidation than that for plasma pre-oxidation and there is no difference in the p-Ge MOS capacitors. This result indicates that slow traps near the Ge conduction band side are additionally generated during the PPO process. Fig. 2 shows that the Al_2O_3/ GeO_x/p-Ge MOS interface has the GeO_x thickness variation of ΔN_{st}, while the Al_2O_3/GeO_x/n-Ge MOS interface has no dependence. These results indicate that slow traps for electrons and holes exist at different positions in the Al_2O_3/GeO_x/Ge MOS interfaces. As seen in Fig. 3, ΔN_{st} of the Al_2O_3/GeO_x/n- or p-Ge MOS interfaces is significantly lower than those of the MOS interfaces with the other high-k films. These results clearly show that the ALD Y_2O_3, HfO_2 and La_2O_3 films introduce additional slow traps in the high-k/GeO_x/Ge gate stacks in comparison with Al_2O_3. Finally, we schematically summarize possible locations of slow traps in the Al_2O_3/GeO_x/n- and p-Ge MOS interfaces and Y_2O_3, HfO_2 and La_2O_3/GeO_x/n- and p-Ge MOS interfaces with plasma pre-oxidation in Fig. 4. The slow traps for electrons can locate near the GeO_x/Ge MOS interfaces [7-8], as shown in Fig. 4(a). On the other hand, the slow traps for holes can locate around the Al_2O_3/GeO_x interface, shown in Fig. 4(b) [8]. The slow trap energies for holes and electrons seem similar to the calculated ones of oxygen vacancies in Al_2O_3 [9] and valence alternation pair (VAP) defects in GeO_2 [10], respectively, as shown in Fig.4. On the other hand, the higher slow trap density in Y_2O_3, HfO_2 and La_2O_3/GeO_x/n- and p-Ge MOS interfaces suggest that much larger amounts of additional slow traps for both electrons and holes can locate near the interfaces of GeO_x with ALD Y_2O_3, HfO_2 and La_2O_3, probably inside the high-k films, as shown in Fig. 4(c) and (d).

Conclusion A large amount of slow traps for electrons are additionally generated during the PPO process near conduction band side. The main slow traps in the Al_2O_3/GeO_x/Ge interfaces can locate near the GeO_x/Ge interfaces for electrons and near the Al_2O_3/GeO_x interfaces for holes. However, replacing the high-k materials from Al_2O_3 to Y_2O_3, HfO_2 or La_2O_3 can change the physical origins of the slow traps origins into any defects inside high-k or around high-k/GeO_x interfaces.

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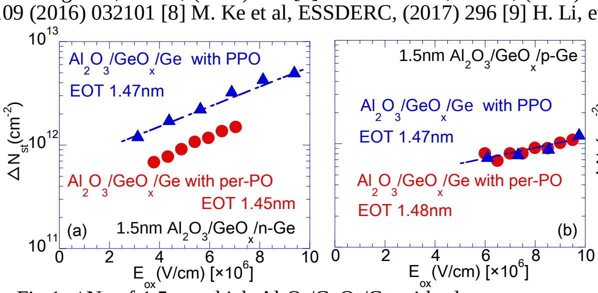

Fig.1: ΔN_{st} of 1.5-nm-thick Al_2O_3/GeO_x/Ge with plasma post or pre-oxidation with an EOT ~1.5-nm-thick

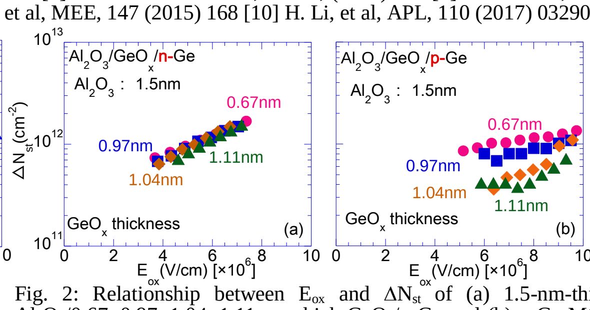

Fig. 2: Relationship between E_{ox} and ΔN_{st} of (a) 1.5-nm-thick Al_2O_3/0.67, 0.97, 1.04, 1.11-nm-thick GeO_x/n-Ge and (b) p-Ge MOS interface with plasma pre-oxidation.

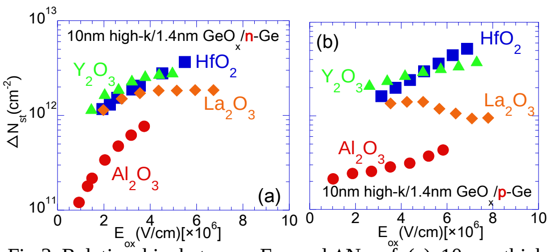

Fig.3 Relationship between E_{ox} and ΔN_{st} of (a) 10-nm-thick Al_2O_3, Y_2O_3, HfO_2 and La_2O_3/1.4-nm-thick GeO_x/n-Ge and (b) p-Ge with plasma pre-oxidation.

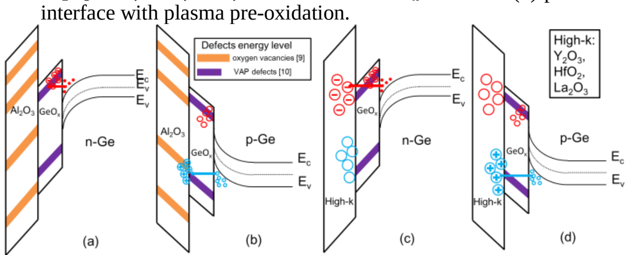

Fig.4 Schematic diagram of possible positions of slow traps of (a) Al_2O_3/GeO_x/n-Ge and (b) p-Ge (c) Y_2O_3, HfO_2 or La_2O_3/GeO_x/n-Ge and (d) p-Ge MOS interfaces by plasma pre-oxidation.

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